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study compares the results from Mie theory with controlled lab experiments. Phytoplankton monocultures and polystyrene beads ranging in size from 0.6 to 160um were used in various concentrations in laboratory tank tests. Here we compare the measured VSF's to theoretical results.

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EVALUATING FORWARD LIGHT SCATTERING MEASUREMENTS

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INTRODUCTION

Forward light scattering can be used for rapid determination of *in situ* particle size distributions (PSD) based on an inversion of the volume scattering function (VSF). One advantage of this technique is that it can capture continuous *in situ* data rather than discrete depth bottle measurements, which are more common and more laborious. To evaluate our ability to measure the VSF, a multi-institution effort was conducted to test the performance of several instruments that measure scattering. This presentation focuses on the performance of two instruments, the VABAM (Variable Aperture Beam Attenuation Meter, WetLabs, Inc.) and the LISST-100 (Laser In-Situ Scattering and Transmissiometry, Sequoia Scientific), that measure forward scatter at small angles. This study compares the results from Mie theory with controlled lab experiments. Phytoplankton monocultures and polystyrene beads ranging in size from 0.6 to 160μm were used in various concentrations in laboratory tank tests. Here we compare the measured VSF's to theoretical results.

INSTRUMENTS

The VABAM measures forward scattered light between 0.11 and 3.2°. The instrument utilizes a collimated light source consisting of three light-emitting diodes (LED's) with wavelengths of 455, 532, and 650nm. Forward scattered light is collected on a ring detector after it has passed through a mechanical iris with a known aperture. Scattering at specific solid angles is determined by the difference of sequential measurements of the light scattered in the circular detector area. A single scan takes approximately 4 seconds. Beam attenuation (acceptance angle 0.1°) is also measured in each scan.

The LISST-100 measures the angular scattering distribution between 0.1-18° at 670nm. The LISST employs a collimated laser diode light source, has a 5 cm pathlength, and a silicon ring detector with 32 log-spaced rings. It does not have a mechanical aperture, so it collects 32 solid angle measurements of forward scattering simultaneously. The LISST also measures optical transmission at an acceptance angle of 0.6°. For a more detailed description of the LISST-100 and its operating principle, see Agrawal, 2000.

The Mie code used in this analysis is a Matlab translation of Bohren and Huffman's FORTRAN code (1983).

THE EXPERIMENT

Multiple instrument inter-calibration experiments were performed at the Patuxent River Naval Air Station in Lexington, Maryland in May and June of 2002. The LISST and the VABAM were mounted in line, along with an *ac*-9 (WetLabs, Inc.) to provide an independent measure of beam attenuation. Polystyrene spheres (Duke Scientific Corporation) and then, phytoplankton monocultures were added to optically pure water to produce a range of known concentrations of particles. The setup was flushed with and then filled with a sample, and measurements were taken simultaneously.

RESULTS

The VSF's obtained from the LISST more closely resemble the theoretical results than the VABAM measurements (Figure 1). In most cases the VABAM underestimates the theoretical VSF by up to two orders of magnitude. The 5µm bead VSF measured by the LISST captures the magnitude and shape of the theoretical VSF, although the strong theoretical resonances are somewhat damped in the real data by the variability in the size of the beads. The LISST also performed well in capturing the VSF of the nearly spherical phytoplankton *Dunaliella tertiolecta* (Figure 1b). Values for the Mie code phytoplankton input parameters of r, the radius, n, the relative index of refraction, and n', the imaginary part of the index of refraction, were 3.16µm, 1.027, and 0.0018 respectively (MacCallum). The 5µm bead input parameters were $r = 2.5$µm, $n = 1.195$, and $n' = 0$. The Mie parameters were not adjusted to fit the measured data.

The VSF is inherently affected by the magnitude of total scattering in the medium. To assess how the instruments perform over a range of particle concentrations, one has to compare the particle volume scattering phase function, $\tilde{\beta}$ of various dilutions of the same particle size. This is possible because the volume scattering function β can be rewritten as the product of the particle phase function $\tilde{\beta}$ and the scattering coefficient b. This separates the volume scattering function into a factor that indicates the strength of the scattering, b, and a factor that describes the angular distribution of the scattering, $\tilde{\beta}$ (Mobley, 1994). So, to remove the effect of particle concentration on the magnitude of the VSF while preserving its shape, one can simply normalize by the scattering coefficient, b. The phase function is a useful parameter in this experiment because if the instruments are measuring the volume scattering function properly, then the phase functions for all concentrations of particles should be equivalent.

We performed a dilution series using 3µm spheres, and normalized the VSF's from the LISST and the VABAM by the scattering coefficient for each concentration. In this case the phase functions all fell closely together for both instruments, except at the lowest concentration where $c = 0.138\text{m}^{-1}$ (Figure 2). The highest beam attenuation

reached in this dilution series was only 1.0124m^{-1}, but in a dilution series with Maalox we reached values of over 3m^{-1}. In that case the LISST still performed well, with low variability between concentrations (c = 0.064 – 3.27m^{-1}). The VABAM performed poorly in the Maalox dilution series, varying by two orders of magnitude in the calculated phase functions (data not shown).

DISCUSSION

The LISST showed the least variability at angles greater than 1 degree, whereas the VABAM showed the opposite trend (Figure 3). The increased error for the LISST at small angles can be attributed to the variability of the presence of large particles, which disproportionately affect the signal at the smaller rings. The variability in the VABAM measurement may be the result of inconsistent aperture alignment between different scans.

The magnitudes of the VSF's measured by the VABAM are over an order of magnitude less than the theoretical results in most cases (Figure 1). Though it does have higher angular resolution than the LISST between some angles (0.2 – 3.16°), the VABAM's narrow angular range limits its functionality in inversion models for estimating a particle size distribution. The VABAM appears to have the advantage of being a spectral instrument, but we were never able to reliably acquire meaningful data with wavelengths other than 650nm. The 532nm channel and especially the 455 channel often produced negative values for the VSF. All data shown are from the 650nm output.

CONCLUSION

We evaluated the performance of two instruments that measure forward scattering at small angles. Various polystyrene spheres and phytoplankton cultures were prepared in optically pure water and were sampled simultaneously by the LISST-100 and the VABAM. The LISST showed closer agreement with Mie theory for both the beads and the phytoplankton. Although the magnitudes of the VABAM measurements were off, both instruments performed well in capturing a consistent phase function over a range of bead concentrations.

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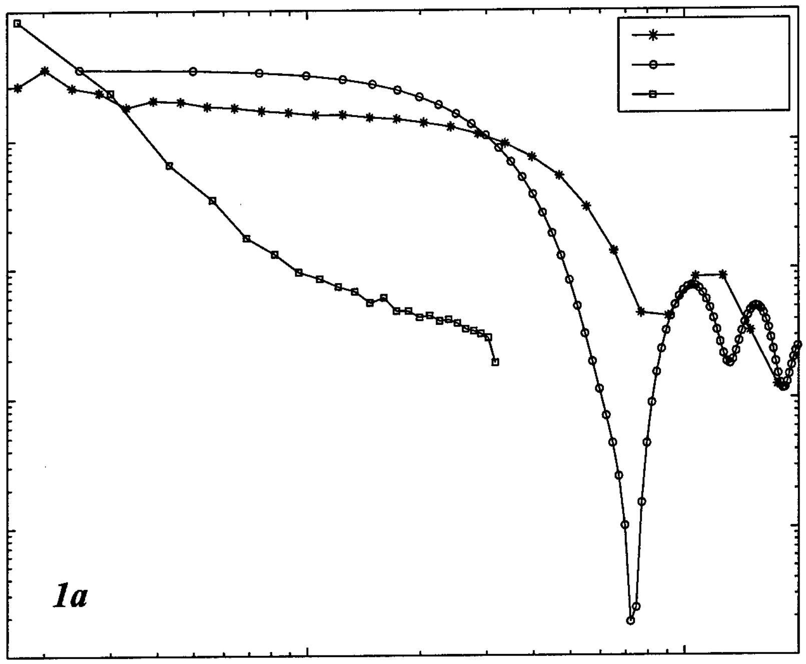


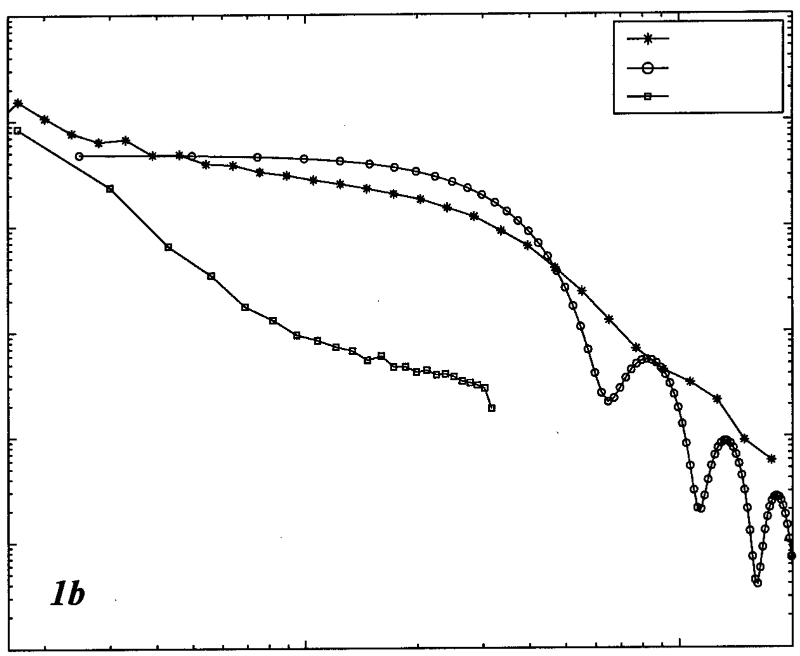


Figure 1. Volume scattering functions from 0.10 – 20° for (a) 5μm polystyrene beads and for (b) Dunaliella tertiolecta as measured by the LISST-100 and the VABAM, and as predicted by Mie theory. Inputs for the Mie calculations were: r=2.5μm, n=1.195, and n'=0 for the beads, and r=3.16μm, n=1.027, n'= 0.0018 for **D. tertiolecta.**

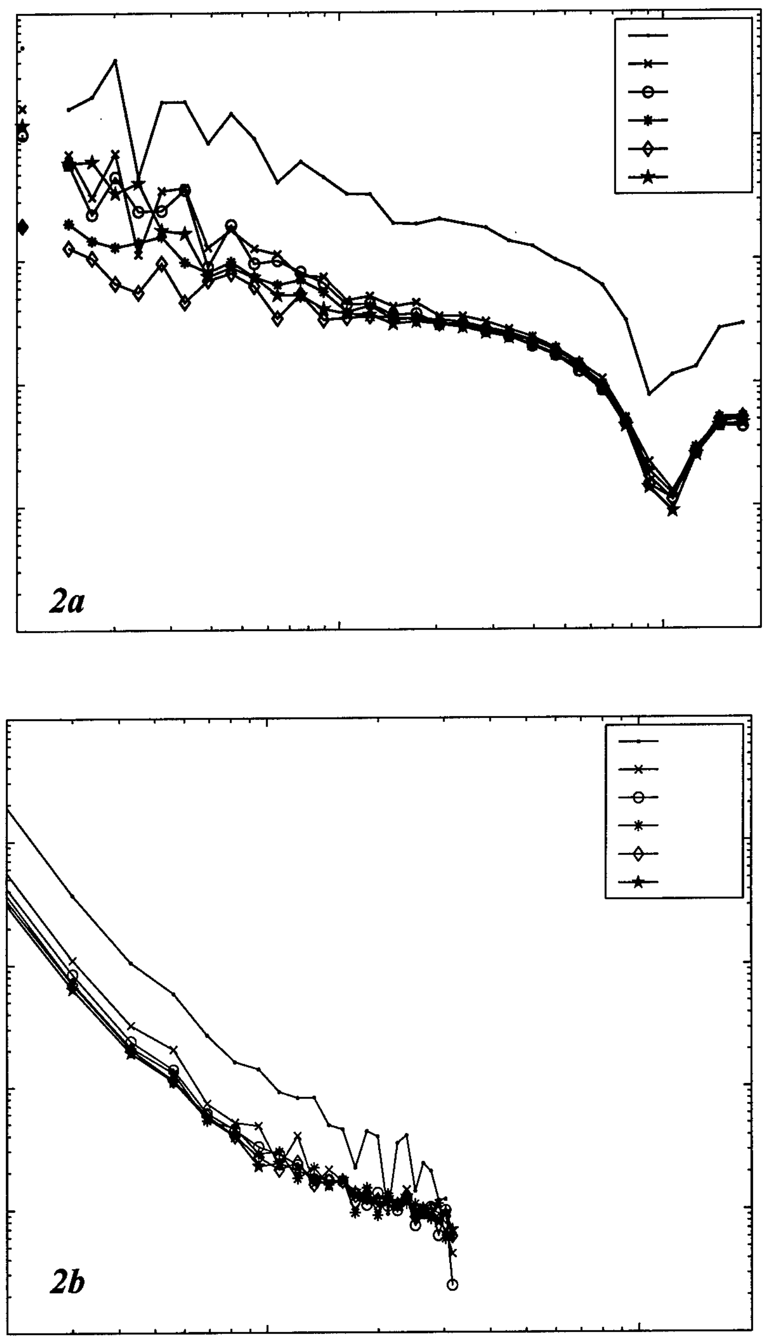


Figure 2. Phase functions measured by (a) the LISST-100 and (b) the VABAM. 'b' values for normalization were taken from the LISST measurement of beam attenuation, assuming that for the beads there was no absorption so b = c. The legend shows the beam attenuation for each concentration.

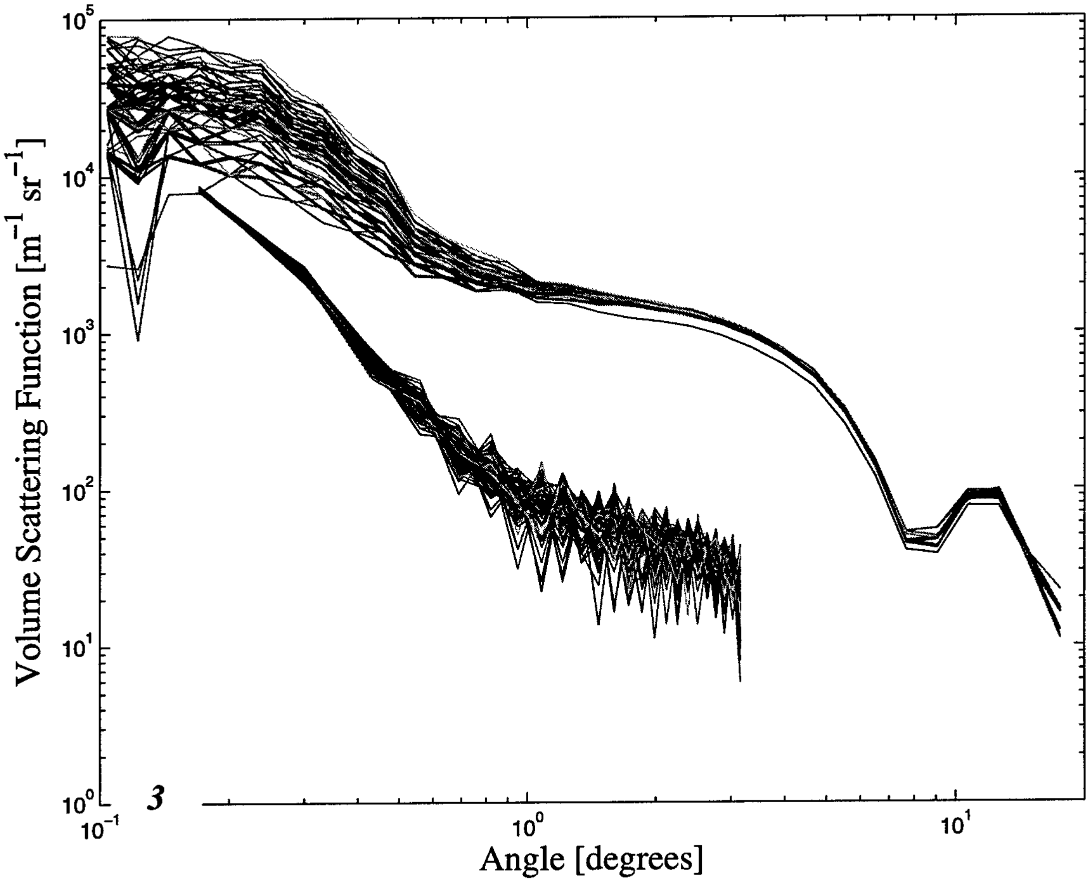
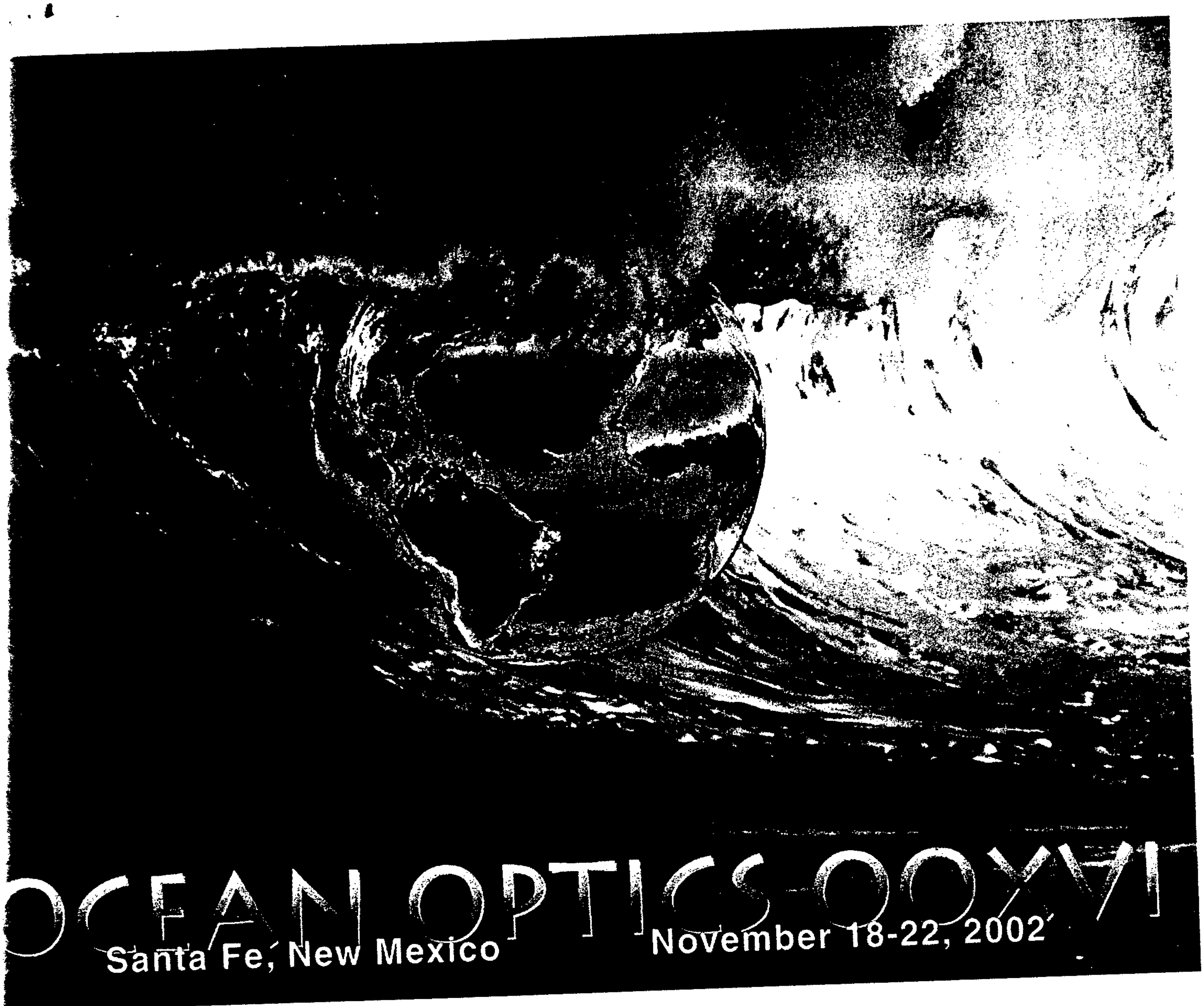


Figure 3. Variability in VSF measurements from the LISST (upper curves, N=100) and the VABAM (lower curves, N=72) for 5μm beads.



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